

Experimental Investigation of the Root Cause Mechanism and Effectiveness of Mitigating
Actions for Axial Offset Anomaly in Pressurized Water Reactors

DOE Contract Number: DE-FG07-02ID14324

Report for the period June 1, 2003 – May 31, 2004

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July 15, 2003

1. INTRODUCTION

Axial offset anomaly (AOA) in pressurized water reactors refers to a significantly larger measured negative axial offset deviation than predicted by core design calculations. The neutron flux depression in the upper half of high-power rods experiencing significant subcooled boiling is believed to be caused by the concentration of boron species within the crud layer formed on the cladding surface. Recent investigations of the root-cause mechanism for AOA (Ref. 1) suggest that boron build-up on the fuel is caused by precipitation of lithium metaborate (LiBO_2) within the crud in regions of subcooled boiling. Indirect evidence in support of this hypothesis was inferred from operating experience at Callaway, where lithium return and hide-out were, respectively, observed following power reductions and power increases when AOA was present. However, direct evidence of lithium metaborate precipitation within the crud has, heretofore, not been shown because of its retrograde solubility. To this end, the goal of this investigation is to examine the root-cause mechanism of AOA, and the effectiveness of possible mitigating actions to limit its impact in high power PWR cores.

Experiments are conducted in a pressure vessel at prototypical PWR primary coolant pressures and temperatures corresponding to core regions experiencing AOA. The concentrations of boron, lithium, and other species in the coolant were controlled and maintained at prototypical values corresponding to beginning-of-cycle conditions. During this reporting period, experiments have been conducted at different pH values with both soluble and insoluble corrosion products (iron and nickel compounds) to accelerate crud deposition. Electrically-heated Zircaloy-4 test elements were immersed in the coolant for specified periods of time, while maintaining them at various surface heat fluxes up to $5 \times 10^5 \text{ Btu/hr-ft}^2$ ($\sim 1.6 \text{ MW/m}^2$); these heat fluxes are comparable to those present at the hot spot in a modern PWR core. At the end of each experiment, the test elements were rapidly isolated from the coolant, while maintaining their surface temperatures constant, thereby preventing the dissolution of any lithium metaborate, which may be present within the crud, without causing surface burnout. Experiments were conducted at different values of surface heat flux, pH, and soluble and insoluble iron and nickel concentrations. Most experiments conducted during this period were operated at the highest possible surface heat flux for a period of five weeks (each) to increase the opportunity for crud formation and boron deposition. Upon conclusion of the experiments, the surfaces were examined to identify the boron hideout species, verify the presence or absence of lithium metaborate, and quantify the amount of crud and boron-bearing material deposited within it.

The quantitative data obtained in this investigation can be used to verify the accuracy of any physically-based mechanistic models aimed at describing the transient processes taking place in high heat flux subcooled boiling regions of the core as it progresses through an AOA scenario. It should also aid in evaluating the efficacy of alternate pH control programs, and the effect of soluble and insoluble species on crud deposition.

In addition, these studies are used to train and educate students in areas of direct engineering interest to the nuclear power industry, including reactor operations, thermal-hydraulics, reactor chemistry, and core physics. Additionally, they provide the students with the opportunity to utilize state-of-the-art analytical techniques such as EDX, XRD, SIMS, and ICPMS. During this reporting period, one Nuclear Engineering student has completed his MS thesis.

2. OBJECTIVES AND SCOPE OF EFFORT

The purpose of this investigation is to experimentally identify the nature of the boron hideout species associated with AOA in pressurized water reactors; such direct evidence will either support or refute the proposed root-cause mechanism based on LiBO_2 deposition within the crud. In addition, the experiments can provide the necessary experimental database to validate models for crud deposition rates, as well as the net rate of boron deposition within the crud as a function of crud layer characteristics, exposure time, and operating conditions. Additionally, the effectiveness of various mitigating features to limit the extent of crud formation and boron deposition therein (i.e. AOA) in high power PWR cores will be explored.

Previous work performed at the Georgia Tech AOA Test Facility showed that the most difficult task in this project is to form a layer of prototypical “crud” on a test element within a reasonable length of time. During this reporting period, the effect of soluble and insoluble corrosion product species on the rate of crud deposition was investigated. In some cases, crud deposition was achieved at rates more than an order of magnitude higher than those in AOA plants. This makes it possible for the experiments to achieve the desired objectives within reasonable exposure times (i.e., several weeks each instead of several months). This, in turn, increases the experimental program yield (i.e. number of data points) and allows testing at a wide range of conditions. In some cases, crud deposition was significantly retarded to levels well below those in actual AOA plants despite operating at extremely high subcooled boiling rates. The wide range of crud deposition rates achieved in the experiments (nearly two orders of magnitude variation) will extend the parameter range for model validation and make it possible to identify appropriate chemistry control schemes to limit crud deposition, and hence AOA, in PWR cores.

Another major objective of this project is to educate graduate students in nuclear engineering who are interested in performing experimentally-based graduate theses in areas of direct relevance to designers and operators of water-cooled reactors as they push the state of the art towards longer operating cycles and higher power cores. Students interested in a wide range of areas, including reactor engineering, boiling heat transfer, mass transfer, corrosion, water chemistry, and reactor operations can directly benefit from such research. Graduate students perform theses research in the following two areas:

- (a) Obtain quantitative data for the rate of boron deposition within the crud under prototypical PWR operating conditions (pressure, temperature, and water chemistry corresponding to different burn-up points along the cycle).
- (b) Quantitatively evaluate the effectiveness of various mitigating actions aimed at limiting the rate of crud and boron deposition, and hence AOA, during extended cycles in high power cores.

In addition to performing hands-on experimental research on a state-of-the-art test facility, the students will be introduced to (and will perform) a wide range of quantitative analyses (EDX, SIMS, ICP-MS, and XRD). These analyses will be performed after each experiment to quantify

the rate of boron deposition and identify the boron “hide-out” species. In addition to educating graduate students in nuclear engineering, the data to be obtained in this research is highly valuable, inasmuch as it will provide the means to validate predictive models for boron deposition within the crud. Such models will guide designers of current and future water-cooled reactor cores as they push towards longer cycles and higher core power densities. The research work performed by the students will serve as the basis for their graduate theses.

In this reporting period, one Nuclear Engineering graduate student involved in this project has completed his MS thesis; a new Nuclear Engineering PhD student has been recruited to perform his thesis research in this area beginning in the Fall of 2004.

3. TEST FACILITIES

The Georgia Tech AOA Test Facility allows experiments to be conducted in a pressure vessel maintained at prototypical primary coolant pressure, temperature, and water chemistry conditions. Boundary conditions, i.e., the surface heat flux, water chemistry, coolant pressure and temperature, can be maintained at the desired values throughout the experiments, which range from several hours to several months in duration. During this reporting period, modifications have been made to the test facility in order to match the coolant velocity within the test vessel (i.e. velocity past the heated surface) to the average velocity within a typical four-loop PWR core. A schematic diagram of the AOA Test Facility is shown in Figure 1.

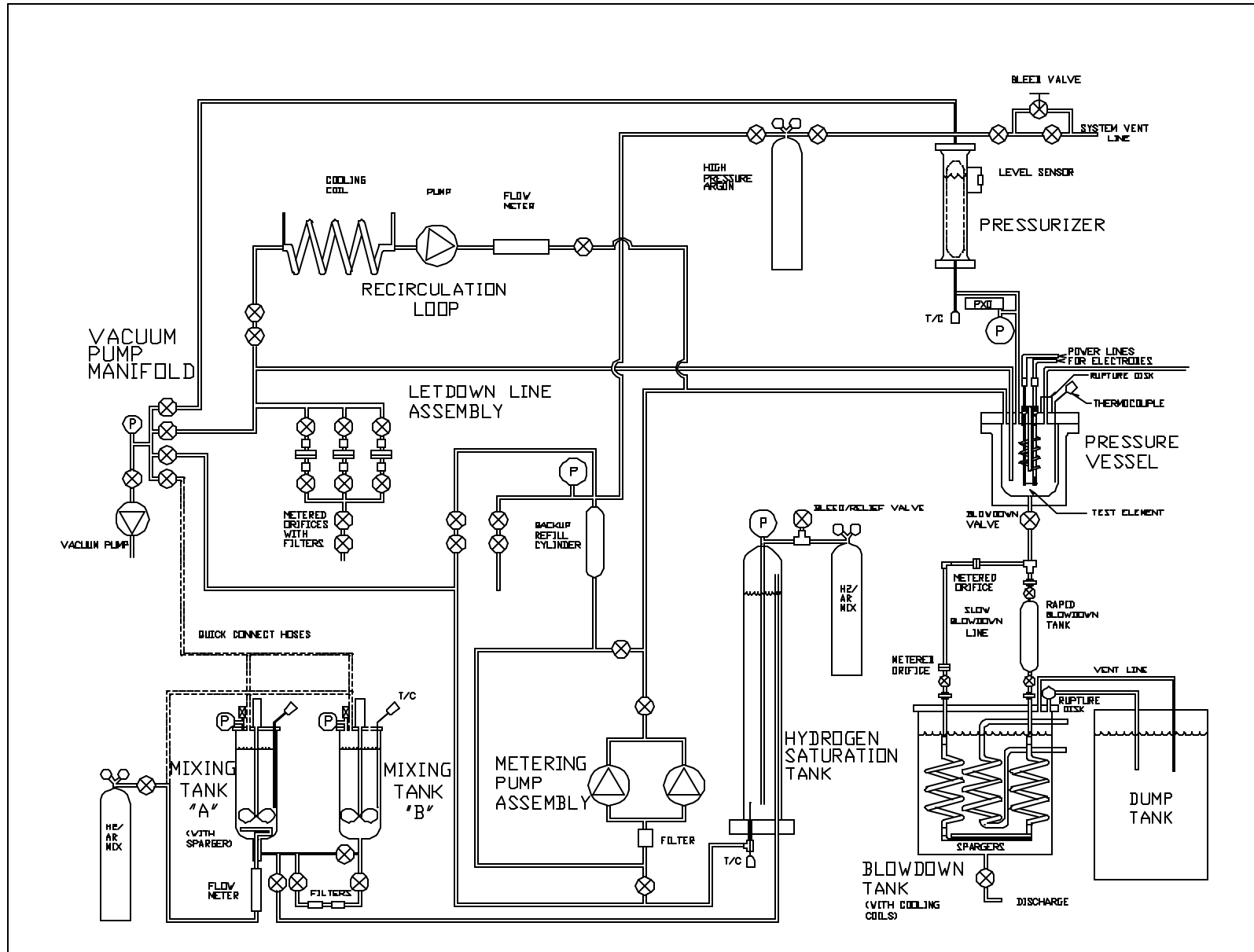
3.1 Test Facility Components

The primary components of the Georgia Tech AOA Test Facility are:

- **Pressure vessel:** A one gallon, 316 stainless steel vessel capable of continuous operation at a working pressure up to 2500 PSIG and temperature up to 650 °F (343 °C). The vessel has a bolted removable top with a graphite spiral-wound gasket seal. The top has eleven threaded ports of various sizes used for electrical feedthroughs, cooling lines, temperature and pressure sensors, etc. The vessel has a 4000 watt heating blanket with a Watlow PID controller, along with an on/off cooling water coil. Vessel temperature can be maintained indefinitely to within one degree Fahrenheit of the desired setpoint.
- **Variable-speed mixer:** In order to duplicate the coolant flow velocities achieved in typical PWR cores, a magnetically-driven variable speed stirrer has been incorporated through the bottom of the pressure vessel. The impeller rotational speed can be adjusted to obtain the desired coolant velocity (~12 ft/s) past the heated Zircaloy-4 test element. The stirrer also assures uniformity of coolant conditions within the vessel; these (time-dependent) water conditions are to be used for model validation.
- **Pressurizer:** A high-pressure tube made of type-316 stainless steel. It contains a hollow titanium float, an electronic level sensor, and a mechanical level indicator. The pressurizer is mounted above the pressure vessel and ensures there is no free surface within the pressure vessel. Argon from a high-pressure gas cylinder provides the desired pressure. A precision gas regulator allows for fine control of the pressure.

- **Blowdown Tank:** A large, low pressure stainless steel tank located below the pressure vessel. The blowdown tank allows for the rapid draining of the pressure vessel. This tank is filled with water and has spargers and a large cooling coil to handle the flashing superheated liquid discharged from the pressure vessel during the blowdown process at the end of an experiment.
- **Hydrogen Saturation Tank:** A long, slender vertically-mounted stainless steel tank used to saturate the coolant with hydrogen before pumping it into the pressure vessel. A hydrogen/argon mix is continuously bubbled through the coolant stored within the saturation tank at a pressure of 300 PSIG to achieve the desired hydrogen concentration in the coolant before transferring it to the pressure vessel.
- **Letdown Line Assembly:** An assembly of valves, filters, and metering orifices which allow for the very slow removal of coolant from the pressure vessel for sampling purposes and prior to a rapid blowdown. Redundant letdown lines are used in case a line clogs and to enable filters to be changed without interrupting the letdown procedure.
- **Metering Pump Assembly:** Two high-pressure precision metering pumps (one main, one backup) are used to transfer fresh coolant from the hydrogen saturation tank to the pressure vessel at any time during an experiment. If both pumps were to fail or are being serviced, there is an additional subsystem that allows the transfer of coolant using only high-pressure argon gas.
- **Mixing Tanks:** Two five-gallon stainless steel tanks are used for mixing and degassing coolant at the start of an experiment. The tanks contain a gas sparger to bubble gas through the coolant to remove oxygen. The tanks have heating blankets and air-motor driven mixing paddles. The tanks can be evacuated using a vacuum pump and can be pressurized with argon or a hydrogen/argon mix during the coolant preparation and transfer processes.
- **Vacuum Pump Manifold:** An assembly of valves and stainless steel tubing connected to a laboratory vacuum pump. Any portion of the AOA Test Facility may be evacuated using this assembly. The vacuum pump is used to remove air from the piping and tanks before introducing degassed coolant into the system.
- **Instrumentation and Data Acquisition System:** Electronic temperature, pressure, and level sensors are used in the AOA test facility. Information from these sensors is continuously fed into a dedicated computer that records all the readings during an experiment. Data can be collected automatically at a user-specified frequency (typically every 5 minutes) for the entire duration of the experiment. In addition, analog level, pressure, current, and voltage gauges are used to backup the electronic sensors.

Figure 1: Schematic Diagram of the Georgia Tech AOA Test Facility



4. EXPERIMENTAL PROCEDURES

4.1 Coolant Preparation

A fresh batch of coolant was prepared prior to each experimental run with generally eight or twelve liters prepared. Distilled water was carefully weighed and placed into mixing tank "A" (see Figure 1). The water was forced through a series of filters into tank B. The filters removed particulate matter down to one-half micron. The water was filtered a second time as it was transferred from tank B back into tank A.

Tank A was stirred continuously and heated to approximately 200°F. Argon was bubbled through the water using a gas sparger to remove oxygen. Periodically, a vacuum was pulled on the tank to remove gas above the surface of the water and to promote boiling of the water.

After several hours of heating and degassing, boric acid crystals were added to achieve the desired boron concentration (usually 1500 wppm). Early experiments used reagent grade boric acid that met or exceeded purity specifications for boric acid used in PWR plants. Later experiments used ultra-pure (99.9995%) boric acid crystals in an effort to reduce contaminants. A small amount of lithium hydroxide solution was added to achieve the desired pH_T value (generally a lithium concentration of 3.47 wppm was used, but higher concentrations were used in some experiments to either increase the pH or compensate for the effect of soluble corrosion products). In some experiments, soluble corrosion products (iron and nickel compounds) were added to the water to promote crud deposition on the test wire during the relatively-short exposure time of the experiment (five weeks versus more than a year in an actual PWR core). Soluble nickel and iron nitrates and insoluble nickel ferrite were used for that purpose. After adding the soluble chemicals to achieve the desired concentrations, the tank was closed and mixing and degassing continued for several more hours. The mixing and degassing process took nearly six hours to complete.

While mixing and degassing took place in tank A, the hydrogen saturation tank was prepared to receive the coolant. First, it was emptied of all liquid and then evacuated using the vacuum pump. The tank was purged with a 4% hydrogen/96% argon mixture and again evacuated. This was repeated a third time, and then filled with hydrogen/argon at about 30 PSIG. The use of a hydrogen/argon mixture was necessitated by flammability concerns.

When mixing and degassing was completed, all of the coolant was transferred to the saturation tank by pressurizing tank A with argon at 50 PSIG. More hydrogen/argon gas was introduced into the saturation tank until the pressure reached 300 PSIG. This gas mixture was continuously fed to the bottom of the tank and bubbled up through the coolant. Gas was allowed to escape from the top of the tank through a metering bleed valve. Pressure within the tank was maintained at 300 PSIG, and gas bubbled through the coolant for the duration of the experiment. The pressure of 300 PSIG was used to ensure the proper (prototypical) concentration of dissolved hydrogen in the coolant was maintained. The coolant was saturated with hydrogen for a minimum of 24 hours to achieve the desired concentration before it was used in an experimental run.

In some experiments, insoluble corrosion products were added to the coolant after transferring it to the pressure vessel; nickel ferrite was used for that purpose. The purpose of such experiments was to quantify the effect of both soluble and insoluble additives on the rate of crud deposition.

4.2 Test Elements

The test elements used in the experiments are 0.0625 inch diameter wires made of Zircaloy-4, the same material used for cladding fuel rods in many PWR cores; other cladding materials (e.g. Zirlo) were not available. The wire was mounted between electrodes in the pressure vessel and resistively heated by passing a large current through the wire. A new test element was used in each experiment.

All experiments conducted during this reporting period were performed using Zircaloy-4 wires pre-conditioned by oxidation. Earlier experiments indicated that pre-conditioning the wires either by oxidation or deposition of a thin nickel ferrite coating promoted the more rapid growth of a crud layer. This is very important since in-situ formation of crud in a PWR typically takes a year or more. The wire surface was pre-oxidized by baking it in an air atmosphere for 12 hours at 675 °F. Previous experiments used Zircaloy-4 wires pre-conditioned by either oxidation or deposition of a nickel ferrite coating using spray pyrolysis. Details of the spray pyrolysis process and the characteristics of the pre-deposited nickel ferrite coatings were presented in the previous progress report. For the experiments conducted during this reporting period, all crud deposits on the wire were formed in-situ. The wires were bent into a horseshoe shape with flattened loops on each end. This shape gives the wire greater flexibility to handle differential thermal expansion between the wire and the electrodes holding it. The flattened loops create a much greater contact area between the wire and electrodes and reduce incidents of arcing.

4.3 Conduct of a Typical Experiment

Each experiment conducted during this reporting period typically lasted five weeks. The general procedure for these experiments is as follows. While the coolant is prepared as described in section 4.1, the pressure vessel is cleaned and rinsed with distilled water to remove residual contaminants from the previous test run. Prior to installation, the Zircaloy-4 test is weighed to within 10 micrograms in a high-precision Sartorius balance. The wire is attached to the electrodes in the pressure vessel; insoluble corrosion products (nickel ferrite), if any are to be used, are then placed in a porous dispersion device within the vessel before sealing the pressure vessel. Air is evacuated from the pressure vessel and all the piping using a vacuum pump. The system is then purged with argon. Evacuation and purging is repeated two more times to remove air from the system.

Next the coolant is transferred from the hydrogen saturation tank to the pressure vessel and pressurizer. The heating blanket around the pressure vessel is turned on; over the next several hours the temperature in the pressure vessel ramps up to the desired operating temperature, where it is held constant to within ± 1 °F. The desired operating pressure within the system is maintained by supplying argon to the pressurizer from a high-pressure gas cylinder equipped with a precision regulator. Coolant is slowly bled from the system as it expands during the heat-up process in order to control the level in the pressurizer. After the system reaches thermal equilibrium, and the desired inventory, i.e. pressurizer level (typically 90%) is attained, the stirrer is turned on and the impeller rotational speed is adjusted to the desired value. Alternating current supplied to the test element is slowly ramped up until the desired heat flux is reached. The data acquisition program is started and is set to record 20 channels of data from the system at five-minute intervals for the duration of the experiment.

When an experiment is scheduled to be terminated through rapid blowdown of the pressure vessel, coolant is slowly bled from the pressure vessel at the conclusion of the test period until the coolant level is approximately one centimeter above the test element. Pressure and temperature, as well as heat flux, are held constant at normal operating conditions during the several hours it takes to reduce the coolant level to that point.

To initiate blowdown, power to the test element is suddenly cut off. At the same moment, a large drain valve is opened. The very high pressure in the pressure vessel (approximately 2000 PSIG) rapidly forces the remaining hot coolant out of the vessel and into the chilled dump tank. Using this procedure, the test element is rapidly (<70 milliseconds) isolated from the coolant to prevent dissolution of any boron-bearing material (including LiBO_2) which may be present in the crud. After the rapid blowdown, argon is bled into the system to reduce oxidation as the pressure vessel cools from nearly 600 °F to room temperature. When cool, the pressure vessel is opened and the test element is removed.

After an experiment, the test element is examined to verify the presence or absence of LiBO_2 and quantify the amount of boron deposition using a number of different methods (SEM/EDX; SIMS; XRD; ICP-MS). Coolant samples collected during the run are also analyzed.

5. RESULTS

A list of experiments conducted during this investigation is given in Table 1; seven experiments (#31 through 37) were conducted during this reporting period (June 1, 2003 through May 31, 2004). Except for experiment #36, which was terminated after only seven days, each experiment lasted for a period of approximately five weeks (30 to 34 days). Table 1 also includes a list of long-term experiments conducted during the previous reporting period (June 1, 2002 through May 31, 2003); these ranged in duration from 11 to 61 days. All experiments were conducted at high heat flux values $\sim 4.15 - 4.95 \times 10^5 \text{ Btu/hr ft}^2$. The estimated crud thicknesses achieved at the end of these experiments ranged from 4 μm to 165 μm (see Table 2; results for experiments conducted during this reporting period are shaded in gray). These thicknesses are based on the measured change in wire mass at the end of the experiment, along with an assumed crud porosity of 50% and a crud density equal to that for nickel ferrite. Such wide range of crud thicknesses derives from the broad range of conditions at which the experiments were conducted; they should prove valuable in future effort to validate mechanistic simulation models for crud and boron deposition.

All experiments conducted during this reporting period were performed using pre-oxidized test wires which enhanced in-situ deposition of crud. Experiments conducted during the previous year included some with either un-oxidized wires or pre-coated wires with a pyrolysis deposited layer of nickel ferrite. The experiments conducted during this period clearly indicate that crud deposition can be successfully accelerated to reach the conditions observed during actual PWR core operation. It also shows that crud deposition can be significantly retarded by adjusting the water chemistry conditions.

Scanning Electron Microscope (SEM) analysis of in-situ formed crud showed that it was both porous and contained vapor chimneys. (See Figure 2 from experiment 27). The crud layer was up to 165 μm thick. Vapor chimneys 10 to 25 μm in diameter were randomly distributed about

the surface and appeared to extend all the way to the bare wire. Laser-ablation inductively coupled plasma mass spectroscopy (ICPMS) analysis showed that the chimneys extended all the way to the Zircaloy surface; by focusing the laser on one of the chimneys, zirconium was the primary material detected. The chimney structure is consistent with PWR deposits that have undergone significant sub-cooled boiling. The lithium metaborate hypothesis requires that porous deposits provide places for LiBO_2 to accumulate and the chimneys allow vapor formed in sub-cooled boiling areas to escape. The presence of different crystalline structures indicates that more than one compound may have deposited on the wire.

Energy Dispersive X-ray (EDX) analysis of the crud showed its elemental composition often varied from one experiment to another. The components of nickel ferrite, nickel, iron, and oxygen, were generally found, though usually not in the expected ratios. Sometimes other contaminants, most notably copper, were found on the wire during early experiments. It is believed that the copper leached into the coolant from the electrodes. Experiments 31 through 37 used electrodes made entirely of stainless steel, and only trace amounts of copper were detected. Boron was found in the crud in all experiments with significant crud deposition. The crud was mostly composed of iron, nickel, and oxygen with as much as 8% (by weight) boron and small amounts (~1%) of carbon. EDX cannot detect lithium.

Experiments 26, 27, and 28 were promising in that the crud which formed most closely resembled the structure of that seen in crud taken from fuel rods. However, the amount formed was quite small. Accurate and repeatable analysis of its composition using quantitative chemistry techniques, powder x-ray diffraction (XRD), and ICPMS was very difficult. Therefore, exploring means of increasing the amount of crud formed on the wire surface became a priority in experiments conducted during this reporting period. As can be seen in Table 2, the test conditions examined produced average crud thicknesses as high as 165 μm , which met the desired objective.

6. CONCLUSIONS

The formation of in-situ prototypical PWR crud with both the appropriate morphology (porous with boiling chimneys) and composition (primarily nickel ferrite) in a non-radiation environment has been the primary focus of our effort during this period. The Georgia Tech AOA Test Facility has so far been successful in depositing crud layers significantly thicker than those in actual PWR cores exhibiting AOA. A wide range of test conditions produced crud thicknesses varying by nearly two orders of magnitude. This allowed the experiment to produce prototypical PWR crud thicknesses within reasonable exposure times (five weeks versus nearly a year in a PWR core). EDX analyses of the deposited crud showed it to be mostly nickel ferrite with significant amounts of boron (up to 8% by weight). These results clearly indicate that the rapid blowdown technique employed in the experiments can successfully “freeze” the boron species deposited in the crud by subcooled nucleate boiling and prevent them from dissolving in the coolant during the cooldown period.

Current efforts are focused on analyzing the crud deposits using ICPMS and XRD to quantify the lithium-to-boron ratio in the deposits and identify the chemical composition of the deposited boron species.

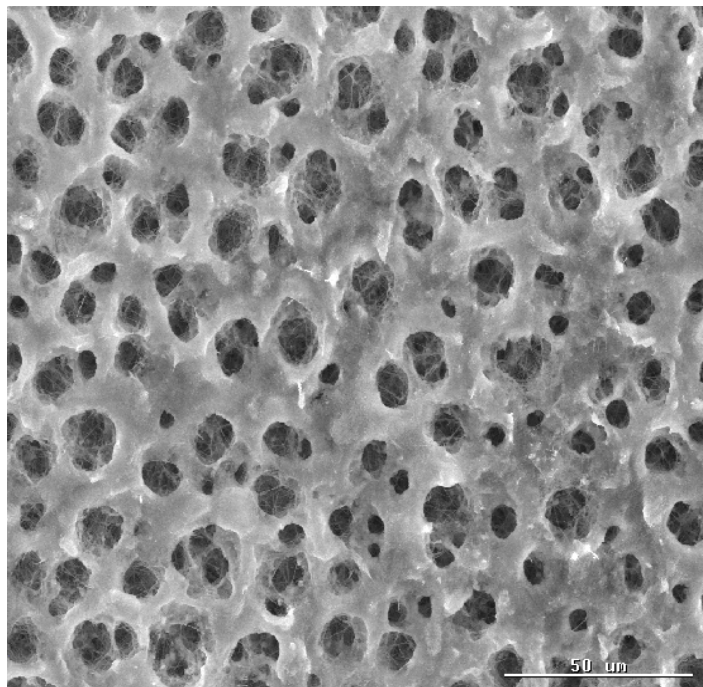
Table 1: Pressure Vessel Experiments Performed

#	Experiment ID	Test Element Type & (Configuration)	Heat Flux (BTU/Hr-Ft ²)	Duration (Days)	Coolant Composition	Notes
25	0628 0726 02	Pre-coated, 4 mil, 50% porosity	375,000	28	1500 ppm B, 3.97 ppm Li	Rapid blowdown; pre-coating came off; Ca/P crud, no B
26	0819 0916 02	Bare Zircaloy-4	430,000	28	1500 ppm B, 5.6 ppm Li, 12.6 ppm Ni, 12 ppm Fe	Rapid blowdown; Crud mostly Ni and Cu; no B found
27	1031 1203 02	Bare Zircaloy-4	445,000	33	1500 ppm B, 5.6 ppm Li, 12.6 ppm Ni, 12 ppm Fe	Rapid blowdown; Crud mostly Ni and Fe; some B and Li found
28	1219 0128 03	Bare Zircaloy-4	430,000	40	1500 ppm B, 5.6 ppm Li, 12.6 ppm Ni, 12 ppm Fe (no H saturation)	Rapid blowdown; Crud mostly Ni, Fe, and Cu; some B found
29	0313 0324 03	Zircaloy-4 w/ spray pyrolysis pre-coat	460,000	11	1500 ppm B, 5.6 ppm Li, 5 ppm Ni, 20 ppm Fe	Wire broke; Crud mostly Ni, Fe, and Cu; some Li, but no B found
30	0328 0414 03	Zircaloy-4 w/ spray pyrolysis pre-coat	440,000	17	1500 ppm B, 5.6 ppm Li, 5 ppm Ni, 20 ppm Fe	Wire broke; Crud mostly Cr and Cu; some B found
31	0527 0630 03	Bare Zircaloy-4 pre-oxidized	415,000	34	1500 ppm B, 5.6 ppm Li, 5 ppm Ni, 20 ppm Fe	Rapid blowdown; Crud mostly Fe, C, and Zr; No B found
32	0801 0902 03	Bare Zircaloy-4 pre-oxidized	460,000	33	1500 ppm B, 5.6 ppm Li, 6.3 ppm Ni, 12 ppm Fe	Wire Broke; high pH
33	0912 1015 03	Bare Zircaloy-4 pre-oxidized	450,000	33	1500 ppm B, 5.6 ppm Li, 6.3 ppm Ni, 12 ppm Fe	Rapid blowdown; high pH
34	0218 0319 04	Bare Zircaloy-4 pre-oxidized	470,000	30	1500 ppm B, 5.6 ppm Li, 6.3 ppm Ni, 12 ppm Fe	Rapid blowdown; high pH; included stirrer to match velocity
35	0326 0430 04	Bare Zircaloy-4 pre-oxidized	460,000	34	1500 ppm B, 5.6 ppm Li, 10 ppm Ni, 20 ppm Fe, 0.2 g Nickel Ferrite	Rapid blowdown, normal pH; added 0.2g of insoluble Nickel Ferrite; stirrer on
36	0504 0511 04	Bare Zircaloy-4 pre-oxidized	485,000	7	1500 ppm B, 5.6 ppm Li, 10 ppm Ni, 20 ppm Fe	Rapid blowdown; normal pH; only soluble additives; stirrer on; experiment terminated due to excessive leakage
37	0513 0617 04	Bare Zircaloy-4 pre-oxidized	495,000	34	1500 ppm B, 5.6 ppm Li, 10 ppm Ni, 20 ppm Fe	Rapid blowdown; normal pH; only soluble additives; stirrer on

Table 2: Crud Deposition Data for Pressure Vessel Experiments

Exp #	Wire Mass Gain (mg)	Deposit density (mg/dm ²)	Deposit Thickness (μm)	Exp #	Wire Mass Gain (mg)	Deposit density (mg/dm ²)	Deposit Thickness (μm)
25	-14	--	--	31	25	500	10
26	31	600	12	32	-3	--	--
27	n/a			33	8	200	4
28	214	4,100	81	34	11	200	4
29	125	2,400	48	35	435	8,300	165
30	167	3,200	64	36	20	400	8
				37	40	800	16

Figure 2: SEM Photograph for crud produced during Experiment #27.



7. REFERENCES

1. "Proceedings of the Axial Offset Anomaly (AOA) Workshop", EPRI Report TR-1000137, June 2000.